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TECHNIQUES FOR REAL-TIME OPERATION OF FLOOD CONTROL RESERVOIRS IN THE MERRIMACK RIVER BASIN

by

BILL S. EICHERT,
JOHN C. PETERS,
ARTHUR F. PABST

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Techniques being developed to provide decision criteria on a real-time basis for operating the five flood control reservoirs in the Merrimack River basin in central New England are described. The techniques include (a) application of alternative streamflow forecasting models, (b) application of computer program HEC-5C, Simulation of Flood Control and Conservation Systems, to develop decision-criteria for system operation on a real-time basis, and (continued)

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20. ABSTRACT (Continued)

(c) use of computer terminals to enable analysis of alternative forecast and/or decision criteria in both batch mode and interactive applications.

TECHNIQUES FOR REAL-TIME OPERATION OF FLOOD CONTROL RESERVOIRS IN THE MERRIMACK RIVER BASIN

by

Bill S. Eichert,[1] John C. Peters,[2] and Arthur F. Pabst[3]

INTRODUCTION

This paper contains a description of the techniques that are under development at The Hydrologic Engineering Center for providing decision criteria on a real-time basis for operating the five flood control reservoirs in the Merrimack River basin. Techniques under development include:

a. testing of alternative streamflow forecasting models

b. application of computer program HEC-5C, Simulation of Flood Control and Conservation Systems, to develop decision-criteria for system operation on a real-time basis

c. use of computer terminals to enable analysis of alternative forecast and/or decision criteria in both batch mode and interactive applications.

Each of these techniques will be discussed following a brief description of characteristics of the basin, reservoir system and automatic data collection network.

CHARACTERISTICS OF BASIN AND RESERVOIR SYSTEM

The Merrimack River basin is located in east central New England and extends from the White Mountain area of New Hampshire southward into the northeast portion of Massachusetts. The basin is 134 miles long north to south and up to 68 miles wide east to west, the drainage area is about 5,000 square miles, 3,800 of which are in New Hampshire.

The average annual precipitation for the Merrimack River basin varies from about 60 inches in the headwaters to about 40 inches in the southern section, with a basin average of about 45 inches. Precipitation is fairly evenly distributed throughout the year. During winter months the precipitation is mostly in the form of snow, with amounts averaging 70 to 100 inches or more in the north to 45 to 60 inches in the southern areas.

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[1]Director, The Hydrologic Engineering Center

[2]Chief, Training & Methods Branch, The Hydrologic Engineering Center

[3]Hydraulic Engineer, The Hydrologic Engineering Center

[4]Presented at The Hydrologic Engineering Center, Seminar on Real-Time Water Control Management, 17-19 November 1975 at Davis, California.

Floods can occur during any season. The two greatest basin-wide floods occurred in March 1936 and September 1938. The 1936 event resulted from two periods of heavy rainfall about a week apart associated with significant snowmelt. The 1938 flood resulted from intense hurricane rainfall which occurred after a week of almost continual rain.

The reservoir system in the Merrimack basin consists of five reservoirs, all of which are operated almost exclusively for flood control. Drainage areas and flood control storage capacities for the reservoirs are as follows:

Reservoir	Drainage Area sq. mi.	Flood Control Storage ac. ft.	Flood Control Storage in.
Franklin Falls	1,000	150,600	2.8
Blackwater	128	46,000	6.7
Hopkinton	382	70,100	6.5
Everett	64	85,500	
MacDowell	44	12,800	5.4

A schematic diagram of the reservoir system is shown in figure 1. The Hopkinton and Everett reservoirs are joined by a canal to enable diversion from Hopkinton to Everett during flood events. Franklin Falls reservoir has a relatively limited flood control capacity because it was originally anticipated that another reservoir would be developed upstream.

Population centers in the basin are located, for the most part, along the main stem of the Merrimack River. For computer simulation runs described in this paper, the locations of Franklin Junction, Concord, Manchester and Lowell were treated as damage centers (see Figure 1). The first three centers are in New Hampshire; Lowell is in northern Massachusetts. A major proportion of the total damages occurs at Lowell. The travel time from Franklin Falls to Lowell is about 30 hours.

PRESENT REGULATION PROCEDURES

Because all reservoirs except Franklin Falls contain about 6 inches of flood control storage, a large flood or a series of smaller ones can be stored in four of the reservoirs without spilling. Consequently, current operation procedures require that the outlet works of MacDowell, Blackwater, Hopkinton, and Everett reservoirs be shut off early in a flood event. Because of the limited storage capacity at Franklin Falls, flows are passed through this reservoir up to the channel capacity of 18,000 cfs. Inflows to Franklin Falls are estimated from reservoir rate-of-rise curves; future inflows are based on flows at an upstream location called Plymouth. Once flows at Plymouth have peaked, a release rate for Franklin Falls is established based on the estimated flood volume.

DATA COLLECTION SYSTEM

The New England Division has established a comprehensive data collection network in the Merrimack River basin as well as in several other New England basins. An automatic radio reporting network supplies information on rainfall and river stage directly to a computer in the Control Center in the Division office in Waltham, Massachusetts. Under computer-programmed control, reporting stations can be interrogated singly or as a group at automatically selected time intervals ranging from six hour to one hour periods based on the amount of river flow or rainfall. At present, river stage is reported from ten locations and precipitation from three locations. Also the New England Division is assessing the use of orbiting satellites for relaying information from data collection platforms. Four of these platforms are currently in use in the Merrimack basin.

FORECASTING TECHNIQUES

Streamflow forecasting may be accomplished using a variety of techniques. A relatively simple technique would involve relating the stage at a downstream location to the stage at some earlier time at an upstream station. A relatively sophisticated technique would involve modeling the precipitation-runoff process continuously involving all aspects of the hydrologic cycle deemed significant. Accompanying this range of forecasting sophistication is a range of required data. A simple gage relationship requires only stage or discharge as a function of time. A precipitation-runoff model may require precipitation, water equivalent of a snow pack, air temperature, dewpoint, wind velocity, insolation, albedo, soil moisture, frost depth as well as streamflow discharge. Forecasting by a simple model is severely limited in its capability to provide information very far into the future. The sophisticated precipitation-runoff model may utilize forecasted meteorological conditions and provide forecasts of runoff as far as is reasonably possible into the future.

The selection of a particular technique will depend on a realistic assessment of the actual data available, the accuracies of the forecast method, and the use that will be made of the forecasted streamflows.

Streamflow Extrapolation Forecasting

A method for making relatively short-term forecasts that utilizes a minimum amount of data would be a useful tool to complement a more complete precipitation runoff model. Initial efforts were directed to development of a simple forecast tool that would require only observed streamflow at various locations in the basin. The technique developed is termed Streamflow Extrapolation Forecasting. In essesnce it is no more than taking observed flows at stream gaging locations, extending them into the future by gage relationships, recessing the flows from that point on, and routing them down the basin.

This technique will be described by use of a simple illustration. Given only the observed flows at stream gage locations A, B, C and D, (Figure 2a) up until the current time, the problem is to estimate the future flows at sites A and B.

The following series of steps would be taken:

(1) Extend the current flows at A, 3-hours into the future based on the immediately preceding flows at A and nearby station C. (Figure 2b)

(2) Recess this hydrograph at A for flows beyond 3 hours into the future. This will provide the forecasted flows at A. (Figure 2b)

(3) Route the forecasted flows at A down to B. (Figure 2c)

(4) Extend the current flows at B, 6-hours into the future based on the immediately preceding flows at B and nearby station D. (Figure 2c)

(5) Subtract the routed flows from A from the extended flows at B yielding incremental local flows between A and B. (Figure 2d)

(6) Recess the incremental local flow beyond 6-hours into the future. This will be the forecasted incremental flows between A and B. (Figure 2d)

(7) Add these incremental flows to the flows routed down from above yielding the forecasted flows at B. (Figure 2e)

(8) Continue downstream as required using the preceding steps.

The gage relationships used in steps 1 and 4, to extend flows at a given station, should be developed from historical data. Multiple regression analysis may readily be used to establish these relationships. A future flow at station A may be correlated to current and past flows at stations A and C. The time span for extending flows (i.e., 3 hours, 6 hours) will depend on the size, shape and other characteristics of the basins.

Such a procedure which assumes little or no future precipitation or snowmelt input, yields the minimum future flows in the river system. If future additional precipitation or snowmelt occur the actual flows will exceed the forecasted flows.

Such a forecast can provide a firm basis for establishing that a reservoir will surely fill. It may not give a long lead time as to when a reservoir will fill; but it is free from the uncertainities of having to assess average basin precipitation with sparse data, calculations of snowmelt, or of establishing losses for frozen or partly frozen ground.

The forecasted discharges are interfaced to the reservoir operation model through a data file. This allows the forecast model to run independently of the operation model. As a separate program the forecast can be made once and then several operation policies may be evaluated using the discharges. It is not necessary to fit both the forecast and operation models in computer core at the same time, or to resort to overlays. Any other forecast technique may be used by simply having the alternative model write the appropriately formatted discharge file.

Evaluation of Forecasts

In order to choose between alternative forecasting techniques it is necessary to establish a measure of forecast accuracy. The measure should reflect the error over a certain finite period into the future, recognizing that the error over such a span will change as one proceeds through the event. In addition it would be desirable to aggregate the error over a series of several floods rather than to accept a given technique only on its reproduction of one event.

When historical data are available the Streamflow Extrapolation Forecasting program will provide information on the relative error (eq. 1) and the standard error (eq. 2) over a future time span selected by the user

$$RELERR_i = \frac{\sum_{j=i+1}^{i+\ell} \frac{|Q_j - QOBS_j|}{QOBS_j}}{\ell} \qquad \text{eq. 1}$$

$$STOERR_i = \sqrt{\frac{\sum_{j=i+1}^{i+\ell} (Q_j - QOBS_j)^2}{\ell}} \qquad \text{eq. 2}$$

where Q is forecast discharge
$QOBS$ is observed discharge
i is current time index
ℓ is future span length of forecast

Such errors can be evaluated at each time period as one steps through the event. The relative errors for the 1936 flood for the Merrimack River at Lowell, MA for two forecast conditions are shown in figure 3. Beneath the actual cumulative local flow hydrograph are shown the errors in a forecast based only on recessed flows at upstream locations, and the errors when station flows are first extended into the future by gage relationships and then recessed. Relatively good agreement was obtained for short term forecasts using this technique.

Another indication of the adequacy of the forecast can be measured in terms of the efficiency of system operation by comparing the results of operation of historical floods with and without forecasts. One measure of this efficiency that may be useful for flood control operation is a comparison of expected (or average) annual flood damages (AAD) using historical flows and forecasted flows. Such a comparison is made in Table 2 where the average annual damage (AAD) for run F-1 is about the same for locations 8, 9, and 10 as the runs using measured streamflow (runs J and 17). The AAD for location 11 is considerably higher for run F-1 than for either run J or 17 indicating additional improvement in forecasting procedures is needed for the location that is substantially further downstream.

RESERVOIR OPERATIONAL MODEL

Basic Objectives of Model

The HEC-5C program was initially developed to assist in planning studies required for the evaluation of proposed changes to a system and to assist in sizing the system components for flood control and conservation requirements. However, the program can also be used in studies made immediately after a flood to calculate the preproject conditions and to show the effects of existing and/or proposed reservoirs on flows and damages in the system. Special features have been added to the program to make it useful for real-time applications. The program logic is designed to minimize flooding as much as possible and yet empty the system as quickly as possible while maintaining the proper balance of flood control storage among the reservoirs.

The above objectives are accomplished by simulating the sequential operation of various system components of any configuration for short interval historical or synthetic floods or for long duration nonflood periods, or for combinations of the two. Specifically the program may be used to determine:

a. Releases from reservoirs during flood emergencies based on local flow forecasts furnished to the program.

b. The evaluation of operational criteria for both flood control and conservation for a system of reservoirs.

c. The influence of a system of reservoirs, or other structures on the spatial and temporal distribution of runoff in a basin.

d. The expected (or average) annual flood damages (AAD), system costs, and excess flood benefits over costs.

e. Flood control and conservation (including hydropower) storage requirements of each reservoir in the system.

f. The determination of the system of existing and proposed reservoirs or other structural or nonstructural alternatives that results in the maximum net benefit for flood control for the system by making simulation runs for selected alternative systems.

Basic Data Requirements

The input data requirements for any basin for HEC-5C can be minimal for preliminary planning studies or detailed for modeling existing systems. The minimum data requirements are as follows:

a. General Information (4 cards)

(1) Title cards for job (3 cards)

(2) Six miscellaneous items including the number of periods of flow data, time interval of flows, etc.

b. Reservoir Data (4 cards per reservoir)

(1) Reservoir capacities for top of conservation and top of flood control elevations.

(2) Downstream control points for which reservoir is to be operated.

(3) Reservoir storage/outflow tables.

c. Control Point (including reservoirs) Data (3 cards per control point)

(1) Identification number and title

(2) Operating channel capacity

(3) Channel routing criteria (Muskingum, modified Puls, Working R/D, Tatum, or Straddle-Stagger)

d. Flow Data

Inflow or local flow data (or observed flows and reservoir releases) for each control point for one or more historical (including forecasted flows) or synthetic floods.

Optional data on flood damages may also be used by inputting peak discharge-damage data where flood damages are directly related to maximum stage (or discharge) obtained during a flood event.

General Operational Criteria for Model

a. Reservoirs are operated to satisfy constraints at individual reservoirs, to maintain specified flows at downstream control points, and to keep the system in balance. Constraints at individual reservoirs are as follows:

(1) When the level of a reservoir is between the top of conservation pool and the top of flood pool, releases are made to attempt to draw the reservoir to the top of conservation pool without exceeding the designated channel capacity at the reservoir or at downstream control points for which the reservoir is being operated.

(2) Releases are made equal to or greater than the minimum desired flows when the reservoir storage is greater than the top of buffer storage, and or equal to the required flow if between level one (top of inactive pool) and the top of buffer pool. No releases are made when the reservoir is below level one. Releases calculated for hydropower requirements* will override minimum flows if they are greater than the controlling desired or required flows.

(3) Releases are made equal to or less than the designated channel capacity at the reservoir until the top of flood pool is exceeded, then all excess flood water is dumped if sufficient outlet capacity is available. If insufficient capacity exists, a surcharge routing is made. Input options permit channel capacity releases (or greater) to be made prior to the time that the reservoir level reaches the top of the flood pool if forecasted inflows are excessive.

(4) The reservoir release is never greater (or less) than the previous period release plus (or minus) a percentage of the channel capacity at the dam site unless the reservoir is in surcharge operation.

b. Operational criteria for specified downstream control points are as follows:

(1) Releases are not generally made (as long as flood storage remains) which would contribute to flooding at one or more specified downstream locations during a predetermined number of future periods except to satisfy minimum flow and rate-of-change of release criteria. The number of future periods considered is the lesser of the number of reservoir release routing coefficients or the number of local flow forecast periods specified on input data.

(2) Releases are made, where possible, to exactly maintain downstream flows at channel capacity (for flood operation) or for minimum desired or required flows (for conservation operation). In making a release determination, local (intervening area) flows can be multiplied by a contingency allowance (greater than 1 for flood control and less than 1 for conservation) to account for uncertainty in forecasting these flows.

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*No Corps hydropower projects are in the Merrimack River Basin.

c. Operational criteria for keeping a reservoir system in balance are as follows:

(1) Where two or more reservoirs are in parallel operation above a common control point, the reservoir that is at the highest index level, assuming no releases for the current time period, will be operated first to try to increase the flows in the downstream channel to the target flow. Then the remaining reservoirs will be operated in a priority established by index levels to attempt to fill any remaining space in the downstream channel without causing flooding during any of a specified number of future periods.

(2) If one of two parallel reservoirs has one or more reservoirs upstream whose storage should be considered in determining the priority of releases from the two parallel reservoirs, then an equivalent index level is determined for the tandem reservoirs based on the combined storage in the tandem reservoirs.

(3) If two reservoirs are in tandem (one above the other), the upstream reservoir can be operated for control points between the two reservoirs. In addition, when the downstream reservoir is being operated for control points, an attempt is made to bring the upper reservoir to the same index level as the lower reservoir based on index levels at the end of the previous time period.

Use of Contingency Allowance and Foresight

Two key input items are used in determining reservoir releases based on downstream flooding as discussed under "operational criteria for downstream control points." These factors are the number of future time periods (IFCAST) that should be checked for possible future flooding (called forecast periods) and the contingency allowance (CFLOD) which is multiplied times the cumulative uncontrolled downstream flow to account for uncertainty in forecasts. For simulation of historical floods (where flows are known for duration of flood) a contingency factor of 1 and an infinite forecast period could be used in order to operate with maximum foresight. However, these assumptions would not simulate "real world" conditions where large errors in forecasting future streamflows are possible. These two key factors, for the simulation of historical floods, should be selected so that the operational efficiencies in the planning mode will approach the expected efficiencies under flood emergency conditions. During flood emergencies these factors should be used to insure that the forecasting errors do not cause reservoir releases to be made which will cause major unnecessary flood damages. The sensitivity of the system to different values of these two factors can be determined by simulating the operation and resulting flood damages for a series of different sized flood events for

the system. The difference between the average annual damages (AAD) for various combinations of these factors will help to evaluate the sensitivity of these factors. Table 1 illustrates how the reservoir system responds to these factors. The adopted value for the number of forecast periods (IFCAST) was four and the adopted contingency factor (CFLOD) was 1.2. Because a time interval of 3 hours was used, the duration of the adopted forecast period was 12 hours.

TABLE 1

AVERAGE ANNUAL DAMAGE VS FORECAST PERIOD
AND CONTINGENCY FACTOR USING HISTORICAL FLOWS

RUN	CFLOD	IFCAST	AAD (in $1000)
1	1.0	2	1191
2	1.0	4	1083
3	1.0	6	1048
4	1.0	10	1070*
5	1.2	2	1116
6	1.2	4	1046
7	1.2	6	1032
8	1.2	10	1052*
9	1.2	20	1099*
10	1.4	2	1082
11	1.4	4	1047
12	1.4	6	1056*
13	1.4	10	1090*
14	1.6	4	1075

*One would expect these values to be less than the previous values. They are not because for the larger events a long forecast period causes reservoir releases to be diminished relatively early in the event. When the reservoirs eventually go uncontrolled, the resulting flooding is greater than would have occurred if the releases had not been diminished early in the event. The increase in damages in the larger events exceeds the decrease in damages for the smaller events.

TABLE 2 - AVERAGE ANNUAL DAMAGES SUMMARY - FORECASTED FLOW

Run	Flood	Total AAD $1000	AAD Location				AAD LOC 11 Flood Ratios					Description
			11	10	9	8	1.4	1.0	.8	.7	.6	
J*	1936	1046	817	146	61	22	373	199	114	122	9	Base Run "J" - Actual Flows CFLOD = 1.2
F1	1936	1345	1120	146	58	21	491	184	118	221	105	Recession Forecast Flows Base Run, CFLOD = 1.2
F2	1936	1286	1052	151	61	23	500	198	113	188	52	Recession Forecast Flows Base Run, CFLOD = 1.4
F3	1936	1307	1072	152	61	22	500	191	117	196	68	Extension Forecast Q Base Run, CFLOD = 1.2
17*	1936	1304	1088	140	60	16	349	199	140	271	128	Base Run, 18,000 rel-res 1, w/o op 11, pre-rel

*From Table 4 using measured streamflows instead of forecasted streamflows

Use of Forecasted Flows

If flow forecast models are available, the same type of simulation runs can be made to determine the proper forecast period and contingency factor by using forecasted streamflow for one or more historical floods and one or more ratios of those floods to calculate the average annual damages. In most cases, the best operation should occur where the average annual damages are a minimum. Table 2 illustrates results using forecasted flows. The adopted values for the forecast period (IFCAST) were four 3-hour periods and contingency factors (CFLOD) were assumed as 1.2 and 1.4 respectively. Results indicate forecast flows are generally adequate for locations 8, 9, and 10, but not at location 11.

The adopted values for historical floods (where future flows are known) should not necessarily be the same as the adopted values during flood emergencies since the forecasted flows will not be the same as the observed historical flows. In general, the contingency factor for historical floods should be selected to produce the same AAD as the run using forecasted flows. The number of periods of foresight should be the same regardless of the source of flows.

OPERATIONAL CRITERIA FOR MERRIMACK BASIN

An essential task associated with computer simulation of the Merrimack reservoir system is evaluation of input parameters for computer program HEC-5C to obtain the most desirable operation of the system. Some of the key input parameters are listed in Table 3. Alternative operation criteria were evaluated by determining average annual damages based on spatial and temporal runoff variations associated with the March 1936 and September 1938 flood events. While average annual damage is a useful criteria for selecting operating policies, other factors such as legal and political considerations must also be used in the evaluation. The procedure used in HEC-5C for estimation of average annual damages is as follows:

a. Ratios are determined for application to selected historical flood events that are representative of the full range of frequency of flood occurrence. For example, ratios of 1.4, 1.0, 0.8, 0.7 and 0.5 were applied to inflow and local flow hydrographs for the March 1936 flood to obtain five floods for which system operation was to be simulated. Frequencies associated with peak discharges for the five floods were determined from frequency curves for unregulated flows for locations where damages were to be computed.

b. Reservoir system operation is simulated for each flood, that is, for each set of inflow and local flow hydrographs obtained by applying ratios to hydrographs for a historical event. Frequencies associated with peak "regulated" discharges are assumed to be the same as the "unregulated" frequencies. Figure 4 illustrates natural and regulated frequency curves for Lowell. Points on the regulated frequency curve in figure 4 represent peak discharges resulting from system simulation for a specific set of operation criteria.

c. Damage-discharge relations input to the computer program enable determination of dollar damages corresponding to the peak discharges at each damage center for each flood. Figure 5 illustrates the damage-discharge relation that was used for Lowell. This is an approximate relation that will be updated in the future.

d. Damage-frequency relations are established for each damage center for both natural and regulated conditions. Figure 6 illustrates these relations for Lowell. The computer program integrates the area below the damage-frequency curves to obtain average annual damages.

The average annual damage calculation is influenced by the distribution of runoff for the historical "pattern" storms. Some characteristics of runoff production for the 1936 and 1938 floods can be ascertained from the hydrographs in Figures 7 and 8. These plots show discharge per square mile for inflow to Franklin Falls reservoir, unregulated flow on the Contoocook river at Penacook and uncontrolled local flow (runoff from all areas downstream from nearest upstream reservoirs) at Lowell.

The 1936 flood reflects high runoff production over the entire Merrimack basin. The flatness of the peak for local flow at Lowell reflects the relatively slow responsiveness of this portion of the basin. Lowell is a key location because a large proportion of total damages occurs there. Consequently, an objective in operating the reservoir system is to try to avoid "building on" the local peak at Lowell.

Figure 8 indicates that runoff production from the Contoocook was relatively high for the 1938 event. However, this portion of the Merrimack basin is 'controlled' with four of the five reservoirs.

TABLE 3

INPUT PARAMETERS FOR HEC-5C

1. Number of periods of future (forecasted) flows that will be used to determine reservoir releases.

2. Contingency factors

These are ratios to be applied to flows in determining reservoir releases; factors are used to account for limited knowledge of future flows beyond the forecast period.

3. Control points for which reservoirs are to be operated.

4. Rate-of-change-of-release criteria for reservoirs.

5. Channel capacity criteria for control points.

6. Minimum release vs reservoir elevation criteria.

7. Pre-release criteria

   a. Whether or not pre-releases will be permitted. A pre-release is a flood-producing reservoir release that is made when the reservoir level is below the top of flood control pool. The release is based on the anticipated flood volume exceeding available capacity.

   b. Reservoir elevation that pre-releases will be geared to.

   c. Magnitude of pre-release permitted (can be specified as a function of reservoir elevation).

RESULTS OF AVERAGE ANNUAL DAMAGE RUNS

In setting up average annual damage runs for HEC-5C, a variety of approaches could be used in selecting floods and flood ratios. For example, one or more ratios of a number of different historical events could be incorporated in a single average annual damage computer run. Another approach is to determine average annual damages for separate sets of ratios applied to individual historical events. Results of these individual average annual damage runs could be weighted depending on how representative individual storms are of the overall flood-producing characteristics of the basin. Two separate sets of simulation runs were made to compute average annual damages for the Merrimack basin. As indicated previously, one set is based on using five ratios of the 1936 event. A second set uses five ratios of the 1938 event.

TABLE 4 AVERAGE ANNUAL DAMAGE SUMMARY

	Run	Flood	Total AAD $1000	Change from Base $1000	Change from Base Percent	AAD Location 11	AAD Location 10	AAD Location 9	AAD Location 8	AAD LOC 11 (Lowell) Flood Ratios 1.4	1.0	.8	.7	.5	Description
A	0	1936	1046	--	--	817	146	61	22	373	199	114	122	9	Base Run[1]
B	1	1936	1074	+ 28	+ 2.7	837	151	63	23	388	211	109*	120*	9	Base Run, w/o RD cards - Res 1 - See Note 2
C	4	1936	1059	+ 13	+ 1.2	841	139*	59*	20*	355*	201	127	148	10	Base Run, RD cards - Res 1 - High Q
D	6	1936	1068	+ 22	+ 2.1	833	149	63	23	384	210	110*	120*	9	Base Run, RD cards - Res 1 - Low Q
E	7	1936	1048	+ 2	+ .2	812*	150	63	23	376	198*	108*	121*	9	Base Run, No Pre-release
F	10	1936	1210	+164	+15.7	994	137*	58*	21*	358	190*	122	214	110	Base Run, w/o operating for loc 11
G	13	1936	1089	+ 43	+ 4.1	839	156	67	27	397	220	95*	118*	9	Base Run, No Pre-release, w/o RD cards
H	14	1936	1207	+161	+15.4	984	141*	60*	22	355*	184*	121	214	110	Base Run, No Pre-release, w/o operating for 11
I	16	1936	1048	+ 2	+ .2	820	145*	61	22	373	199	117	122	9	Base Run, Res 1, level 2 = El 389
Z	17	1936	1304	+258	+24.7	1088	140*	60*	16*	350*	199	140	271	128	Base Run, 18,000 rel-res 1, w/o op Lowell, pre-rel
T	19	1936	1081	+ 35	+ 3.3	858	143*	59*	21*	373	212	128	135	10	Base Run, Pre-Release with Recession
										Flood Ratios 2.0	1.43	1.15	1.00	.70	
A	2	1938	1161	--	--	853	214	67	27	595	186	52	20	0	Base Run
B	3	1938	1164	+ 3	+ .3	853	216	68	27	600	189	48*	16*	0	Base Run, w/o RD cards - Res 1
C															Base Run, RD cards - Res 1 - High Q
D															Base Run, RD cards - Res 1 - Low Q
E	8	1938	1142	- 19	- 1.7	837*	212*	65*	28	592*	174*	51*	20	0	Base Run, No Pre-release
F	9	1938	1193	+ 32	+ 2.8	915	195*	60*	23*	566*	160*	94	93	2	Base Run, w/o operating for loc 11
G	11	1938	1168	+ 7	+ .6	853	217	67	31	604	186	47*	16*	0	Base Run, No Pre-release, w/o RD cards
H	12	1938	1192	+ 31	+ 2.7	915	194*	59*	24*	565*	160*	94	94	2	Base Run, No Pre-release, w/o operating for 11
I	15	1938	1187	+ 26	+ 2.2	891	201*	68	27	483*	193	86	111	18	Base Run, Res 1, level 2 = El 389
Z	18	1938	1200	+ 39	+ 3.3	922	195*	60*	23*	566*	161*	95	97	3	Base Run, 18,000 rel-res 1, w/o op Lowell, pre-rel

NOTES: 1 Base Run - Operating for loc 11, RD cards as shown note 2, Pre-releases, Contingency factor = 1.2, Forecast Period = 12 hours.
2 RD Cards for Res 1 specify min emergency releases as function of reservoir storages.

% F.C. Stg	32	49	75	100 (El 389)	109 (El 394)	112 (El 396)
Base Run Q	0	6,000	12,000	18,000	18,000	30,500
High Q	0	18,000	18,000	18,000	18,000	30,500
Low Q	0	0	6,000	18,000	18,000	30,500

* Improvement over base conditions.

Results of the average annual damage runs are summarized in Table 4. The "base" runs, labeled A in Table 4, were made with HEC-5C input parameters specified as follows.

a. A forecast period of 12 hours; that is, discharges up to 12 hours in the future were considered in determining reservoir releases.

b. A contingency factor of 1.2 was applied to local flows for purposes of reservoir release determination.

c. The reservoir system was operated for all control points shown in figure 1.

d. Rate-of-change of release criteria were specified so as not to be a constraint on releases from Franklin Falls reservoir.

e. Fixed channel capacities were specified for all control points based on information supplied by the New England Division.

f. A table of values for minimum permissible release as a function of reservoir elevation was specified for Franklin Falls reservoir as shown on Table 4 (note 2).

g. Pre-releases were permitted; at Franklin Falls reservoir, pre-releases were made if inflows to the reservoir during the 12-hour forecast period would cause the reservoir level to rise above elevation 394 (5 feet above the spillway crest).

The discharge-damage relation for Lowell (Figure 5) that was input to HEC-5C had a maximum discharge ordinate of 180,000 cfs. Because discharges larger than 180,000 cfs were used in the damage analysis, the discharge-damage relation was extrapolated by the computer program as shown in Figure 5. The effect of using the alternative extrapolation, also shown in Figure 5, on average annual damages was less than 2% for both natural and regulated flows.

Operation criteria for average annual damage runs other than the base runs are summarized in Table 5. Some observations pertaining to results of the average annual damage simulation runs are as follows:

a. Average annual damages based on floods patterned after the March 1936 flood are of approximately the same magnitude as average annual damages based on floods patterned after the September 1938 flood.

b. Operational criteria used for the base run (run A) produced the lowest average annual damages for floods patterned after the March 1936 flood; operational criteria that does not utilize the pre-release option (run E) produced the lowest average annual damages for floods patterned after the September 1938 flood and only slightly more damage for the 1936 flood.

c. Of the order of 75% of the total average annual damages occurs at Lowell on the basis of the approximate stage-damage relationship for that location.

d. Damages associated with very large floods account for a major proportion of average annual damages; this is illustrated in figure 9 which shows the relation between percent of average annual damage and recurrence interval at Lowell for the base run for floods patterned after the March 1936 flood, (e.g., 45% of average annual damages occur under regulated conditions from floods having a recurrence interval of 300 years or greater).

e. Significant discharge and damage reduction at the 1000 year flood level is due to the surcharge storage available in the reservoirs due to the limited discharge capacity of the uncontrolled spillways since the flood control storages were exceeded very early in the largest floods.

TABLE 5

OPERATION CRITERIA FOR SIMULATION RUNS

Run	Criteria
B	Same as for base run, except minimum release not specified for Franklin Falls reservoir.
C	Same as for base run, except relatively large minimum releases were specified (as a function of reservoir elevation) for Franklin Falls reservoir (see note 2 of Table 4 for values).
D	Same as for base run, except relatively small minimum releases were specified (as a function of reservoir elevation) for Franklin Falls reservoir.
E	Same as base run, except pre-releases were not made.
F	Same as base run, except reservoir system was not operated for Lowell.
G	Same as base run, except pre-releases were not made and minimum releases for Franklin Falls reservoir were not specified.
H	Same as base run, except pre-releases were not made and reservoir system was not operated for Lowell.
I	Same as base run, except reservoir elevation of 389 was used at Franklin Falls reservoir for pre-release determination.
J	Same as base run, except minimum releases of 18,000 cfs from Franklin Falls reservoir were specified, system was not operated for Lowell.
K	Same as base run, except the pre-release option was modified to include volume of recession of hydrograph past the period of forecast.

OUTPUT DISPLAYS

Batch Mode vs Interactive Mode

Execution of a computer program in batch mode requires that all input for a computer run be supplied to the computer prior to program execution. An interactive-mode execution is where the user can interact with the computer during the execution of a job. As used in the application described herein, the interactive mode is used to selectively print out data from an output file of the system operation that has been generated in batch mode. This enables the user to review any portion of the output that he desires. The output file can be permanently saved and interrogated at future times from one or more computer terminal sites.

While output displays from high-speed line printers used in the batch mode can provide any amount of output desired, the level of output must be specified prior to making the computer run. Presently, after a run has been made, output not previously requested can only be obtained by making another complete simulation run. An alternative method would be to save the output file and print in batch mode by writing a special program. If the turn-around time is adequate (say less than 30 minutes) and the program execution cost is small, then the batch mode is the best way to get the necessary output assuming that a high-speed printer is available. Where batch mode turn-around times are long, or high-speed printers are not readily available, the slow-speed terminals can be an effective way of obtaining a limited amount of information rapidly. After looking at selected data through the slow-speed terminal the output can then be directed to a high-speed printer if desired.

High-Speed Printer Output

The subroutine PROUT in HEC-5C is used to print output for the high-speed printer (batch mode), slow-speed teletype terminal (interactive mode) and cathode ray tube terminals (interactive mode). All output devices can be used to print any combination of types of output (see samples on Figures 10-11) except for the graphical plots (see Figure 17) available with cathode ray tube terminals. Printer plots (Figure 12) can be requested by the batch mode printers. The types of output that can be requested are as follows:

OUTPUT DESCRIPTION

* Input Card Listing
* Input Flows
* Input Data for System Specification
* Output - Normal Sequential (by control point)
* Output - Reservoirs - by Period
* Output - Reservoir Releases - by Period
* Output - Reservoir Regulation Summary - Single Flood
* Output - Reservoir Regulation Summary - All Floods
* Output - Hydrologic Efficiencies
* Output - Computer Check for Possible Errors
* Batch Economic Summary
* User Designed Output - Results by Period
* User Designed Output - Summary

Interactive Terminal

While the batch mode selects desired output by input cards, the slow-speed terminal asks the user questions, as illustrated in figure 13, concerning what type of function (see Figure 14) should be performed next (output from operation, modify input deck HEC-5C, etc.). If operational output is desired, the type of data (option number of Figure 14) and possibly variable codes and locations, on Figure 15, as well as the output mode (plot, tabulate or save on tape) are required to be specified to the computer. Data can be input to the computer through the terminal by depressing the appropriate terminal keys or (for certain CRT's) by touching an electronic pen to the appropriate instruction (see Figure 15) on a selection list (menu) which lies on a graphic tablet. After the tabulated output (see Figure 16) or plotted results (Figure 17) are obtained, additional data can also be selected and printed as desired. Any combination of data types (reservoir outflow, storage, elevation, downstream flow, etc.) for any location can be tabulated or plotted. Depending on the size of the paper (or screen) up to 10 different items can be tabulated side by side and up to 5 different time dependent variables can be plotted on a single graph. Two different scales can be used for the plots as shown on Figure 17 where the inflow and outflow are plotted on the left scale (discharge) and the reservoir level on the right scale. When all of the desired output has been displayed, the data can be transferred to the line printer at a nearby batch location.

Updating and Reoperation of System

In the batch mode, data cards for the forecast program are read by the card reader and an output file of the forecasted basin-wide flows is obtained. The HEC-5C data cards can be loaded at the same time or at a later time, and the system simulation is performed for the duration of the forecasts and the output is directed to the line printer. Any desired change in the forecast or operation requires a few new data cards and rerunning either the operation model or both the forecast and operation models. Where adequate computer turn-around is available this process can be accomplished in 30 minutes or less.

With a slow-speed terminal the same cycle can be accomplished by using the keyboard or the electronic pen. In addition, high quality graphical displays of the status of the system can be obtained. After the operational data has been displayed, function 5 of figure 14 can be selected and an interactive program called REVISE will allow the revision and/or execution of the data files of either the forecast or operation models. It is then possible to once again display selected output. A diagram of this process is shown as figure 18.

COMPUTER SYSTEMS REQUIRED FOR REAL-TIME OPERATION

In order to reap the benefits of the real-time operation tools described previously, access to digital computer equipment is a necessity. This access may take several different forms depending on characteristics of the data acquisition system, the forecasting and operation models used, and available communications equipment. Real-time water resource operations may make use of only in-house equipment, only remote site equipment, or some combination of each.

The first basic function to be accomplished is that of acquisition of available data. Information required may include observer collected data reported by voice communications and analog or digital signals received by appropriate equipment. Such information may be received over dial-up phone lines, dedicated phone lines, radio repeating links, or satellite repeating links.

When the volume of data is great it is obviously desireable to have the data recorded directly on a medium that may be read by machines. Even more desireable is to have the whole data acquisition function occur under control of a mini-computer. If this is done the mini-computer may also perform several functions such as, error checking, data reduction, permanent logging, report generation, etc. In most cases a mini-computer dedicated to such functions would be required.

Once the data in reduced form (i.e., discharge, precipitation, etc.) is available, the forecast may be performed. Computer equipment for this function will vary depending on the size of the forecast program. Some forecasting models may execute well on the same mini-computer used for data acquisition. Others would require such extensive reprogramming in order to operate on a mini-computer that other alternatives would be desirable. In some cases additional large scale in-house computers may be available. In most cases such facilities will not be directly available to district offices. The use of larger capacity remote site computing becomes very attractive in such a situation. A portion of the reduced data may be sent to the remote site directly by the mini-computer, or read in from paper tape, or magnetic cassette. The forecast may then be performed at the remote site with results returned to the local site and/or saved for future reference at the remote site.

A similar situation exists for executing large system operation programs. Again remote site computing offers a cost effective solution. The forecasted flows may be passed on to the operation model through common access to a data file. Results from the operation routine may then be returned to the local site, or be held for future reference. Display of the results may be performed by the in-house mini-computer, or be handled directly from the remote site.

Problems of using a remote site computing center around two factors; (1) guaranteed access to facilities twenty-four hours per day, three hundred and sixty-five days per year, and (2) reliable communications and power supply even under extremely adverse conditions. It is impossible to guarantee access to any one facility at all times. It is possible however, to have access to several remote facilities and thus provide as high a level of "guaranteed" access as deemed necessary. Communications and power supply which involve ground lines are quite vulnerable to interruption during major storm activity. Backup power supply may be easily supplied by emergency generators.

Backup communications based on a ground network may require an individual to physically carry necessary data to an alternate input site outside the area affected by the communications interruption. An attractive backup for communications which is rapidly being developed is to communicate to the remote site by way of a satellite link.

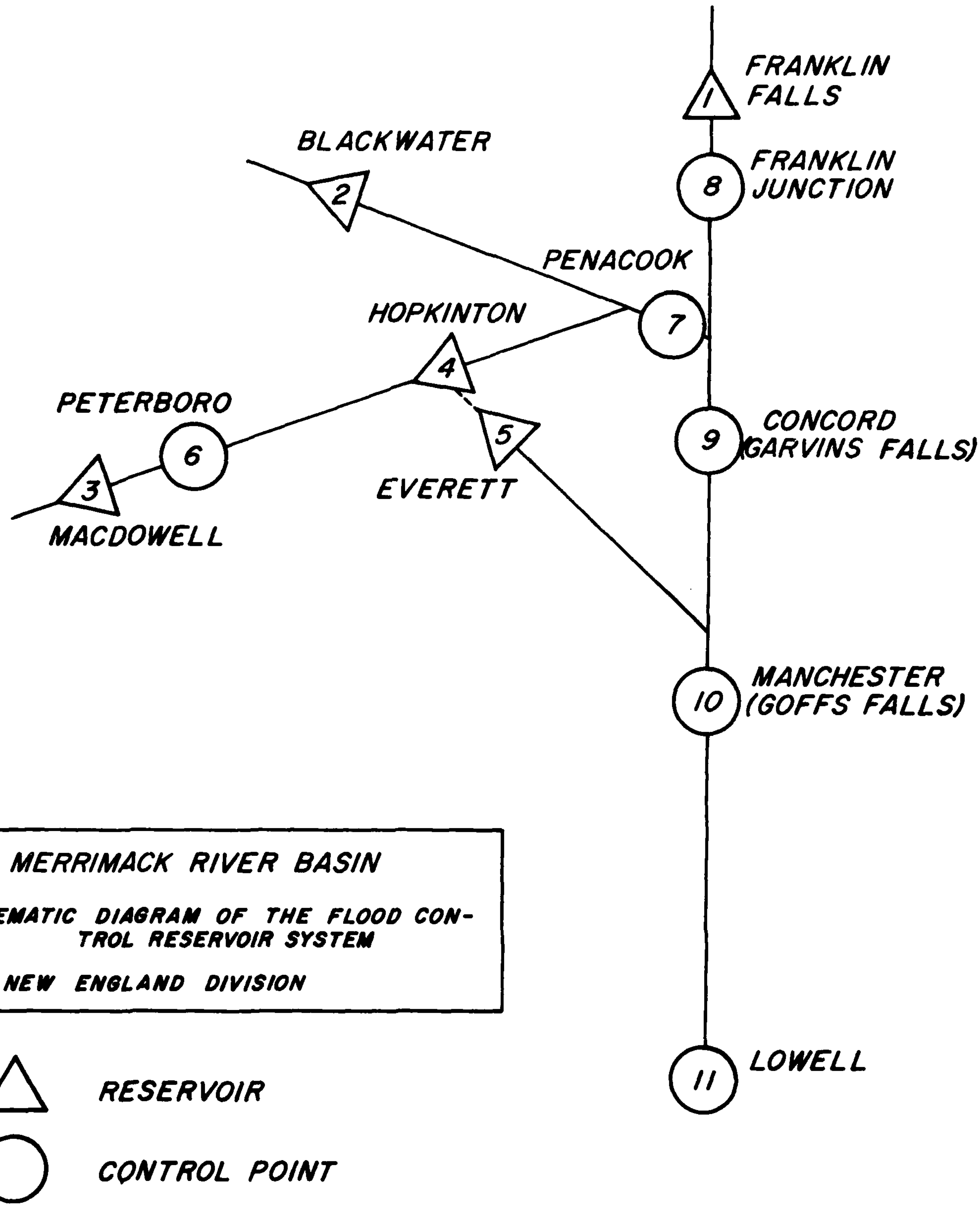
The use of large scale machines for the forecasting and operations aspects of real-time operation are attractive because of the ease of updating or improving the models used. Other modeling techniques may be quickly compared and substituted for those currently in use. When mini-computers are used for executing large programs, changes to the program often entail major restructuring of overlays.

FUTURE WORK

It is planned to implement the forecast-operation-display capabilities described in this paper at the Control Center of the New England Division in the near future. The next step will be to interface these capabilities with the existing automated data collection system.

Alternative forecasting techniques other than the streamflow extrapolation procedure described herein will be tested. Application of the computer program Streamflow Synthesis and Reservoir Regulation (SSARR) developed by the North Pacific Division is anticipated.

The entire procedure for real-time simulation will be thoroughly tested and "fine-tuned" once it is operational at the Control Center.



MERRIMACK RIVER BASIN

SCHEMATIC DIAGRAM OF THE FLOOD CONTROL RESERVOIR SYSTEM

NEW ENGLAND DIVISION

Paper 12

FIGURE 1

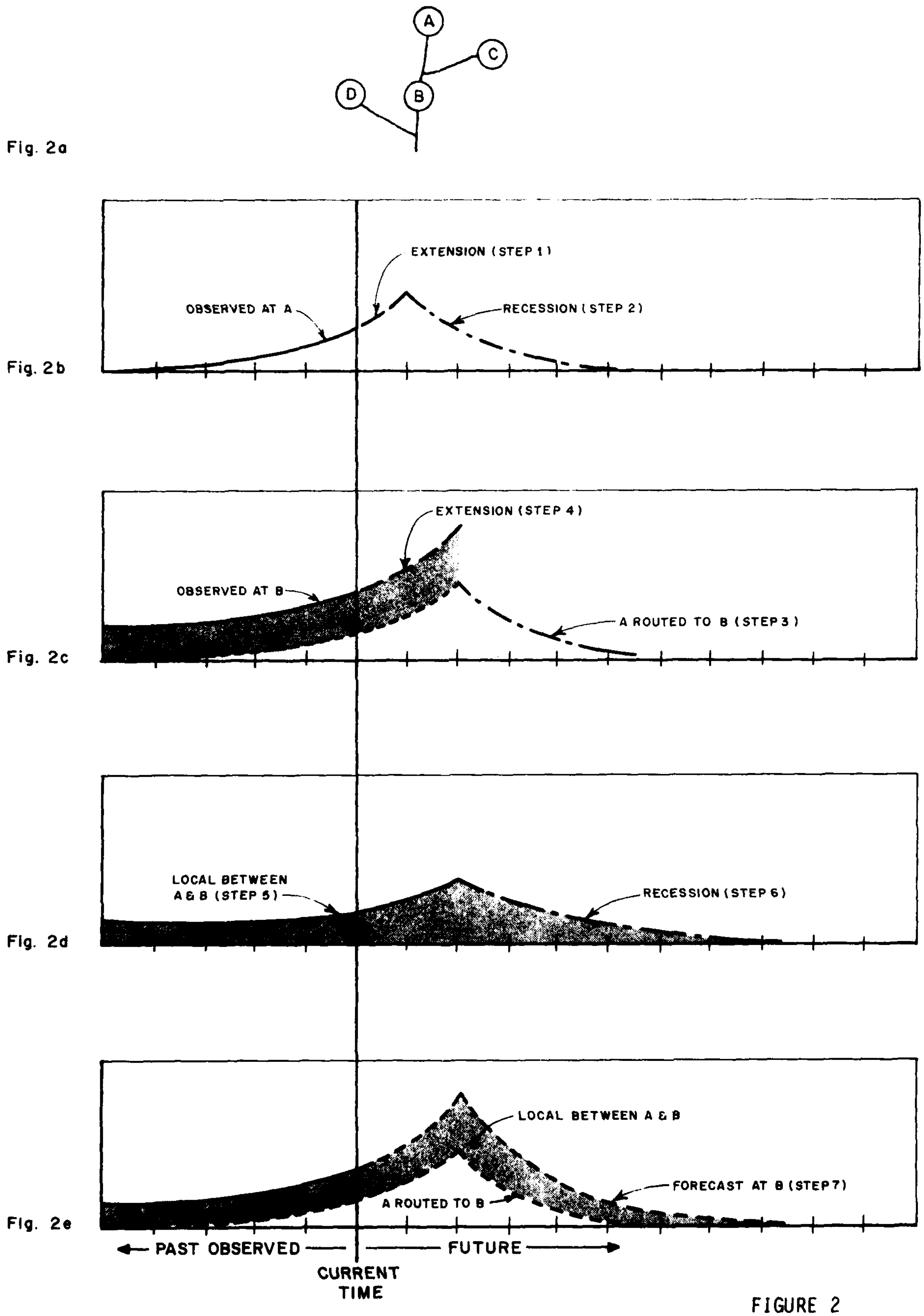
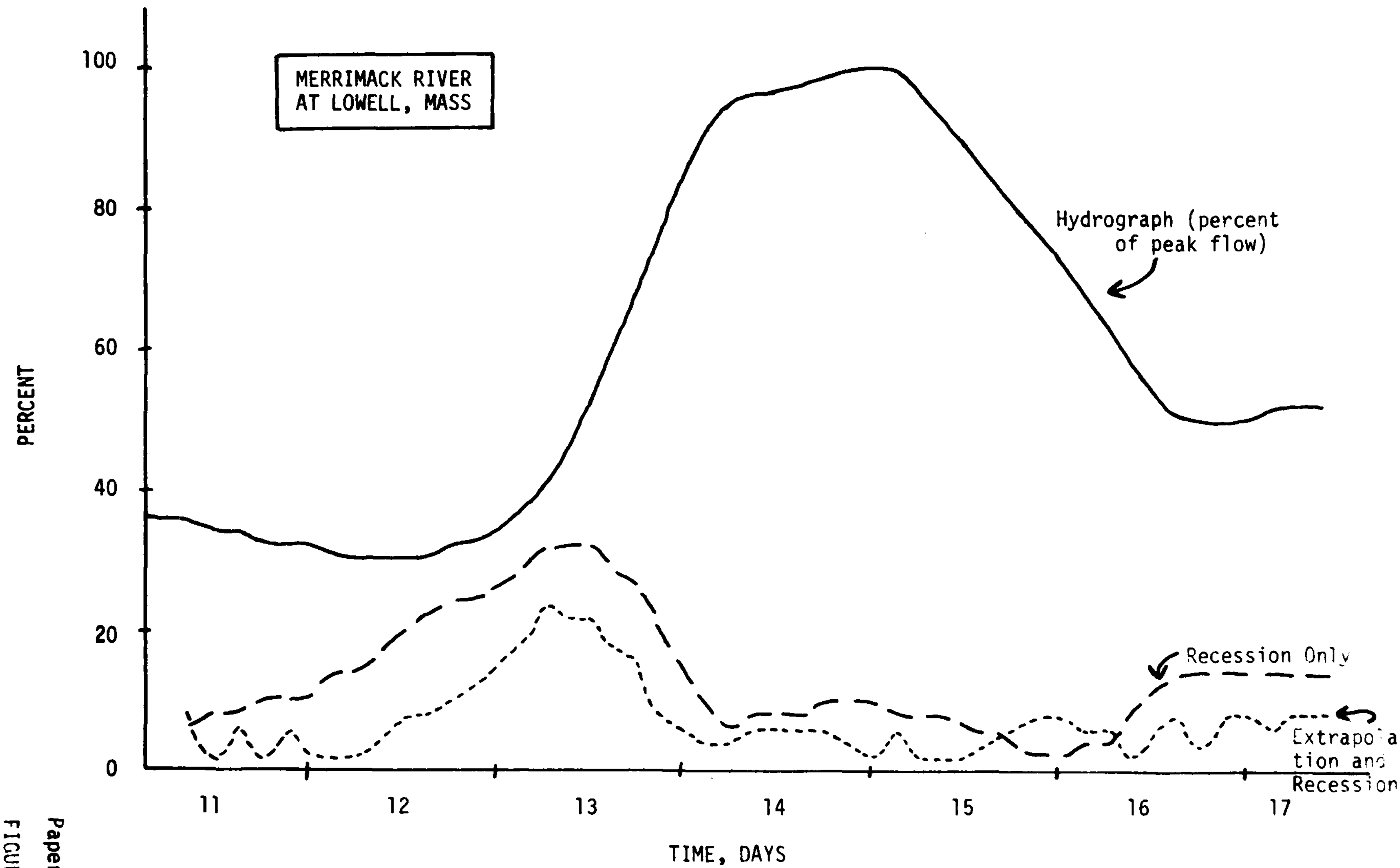


FIGURE 2

Paper 12

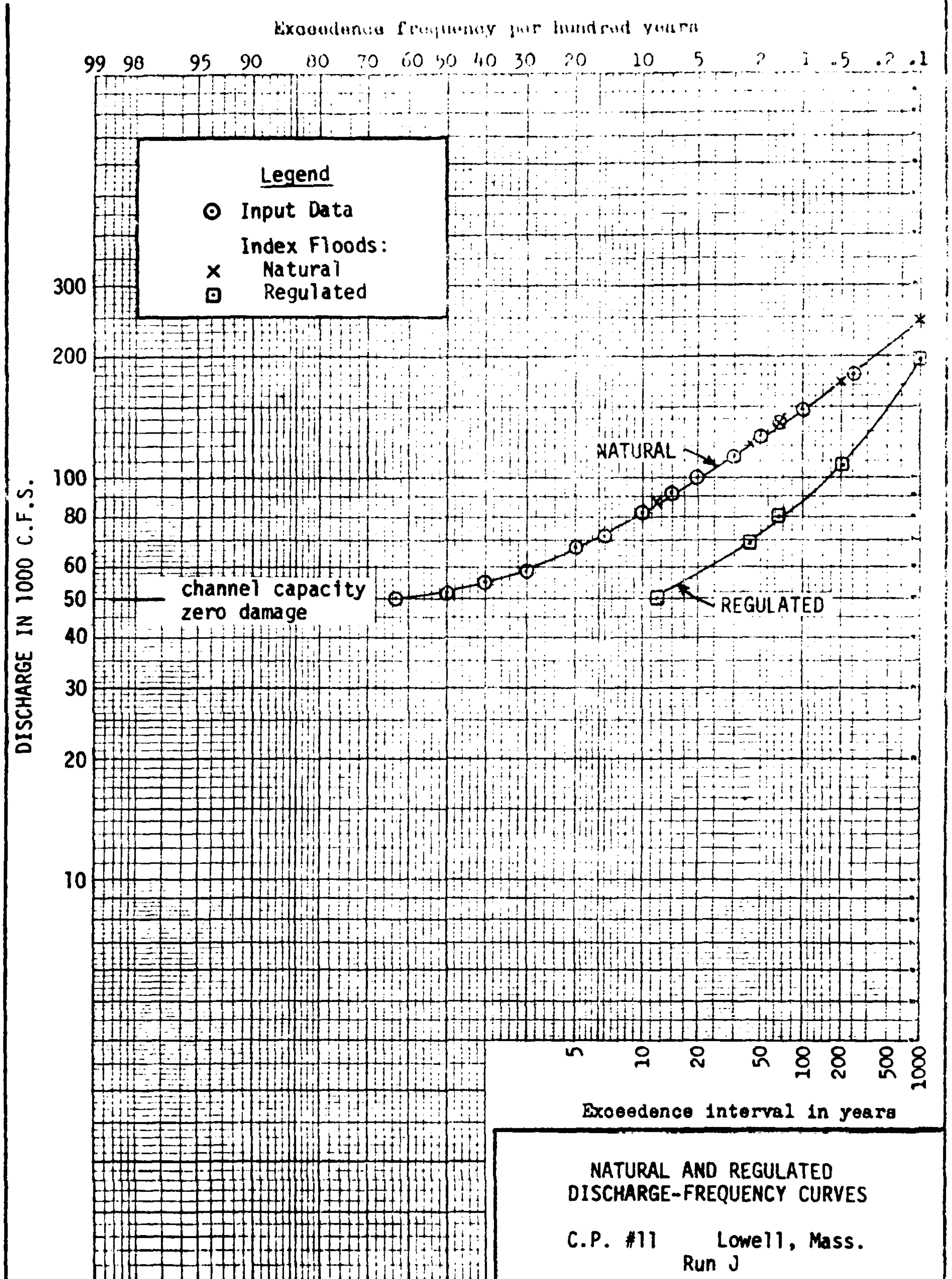
Paper 12

FIGURE 3



Average Relative Forecast Error Over Four Future Periods

Example: At midnight on the 13th, while on the rising limb, the discharge over a span of four future periods (until noon on the 14th) was predicted within 18% by recession only or within 8% by extrapolation and recession.

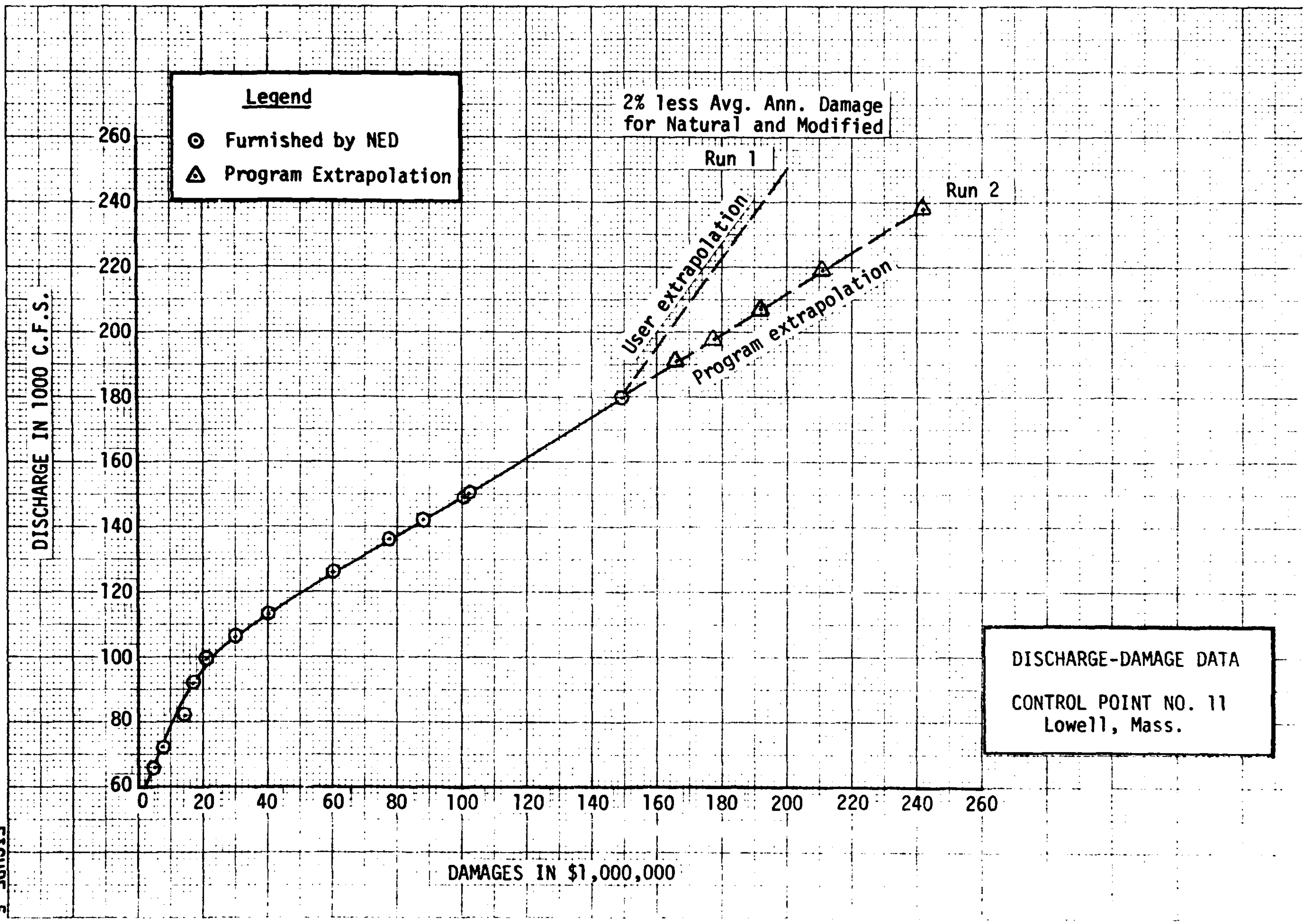


NATURAL AND REGULATED
DISCHARGE-FREQUENCY CURVES

C.P. #11 Lowell, Mass.
Run J

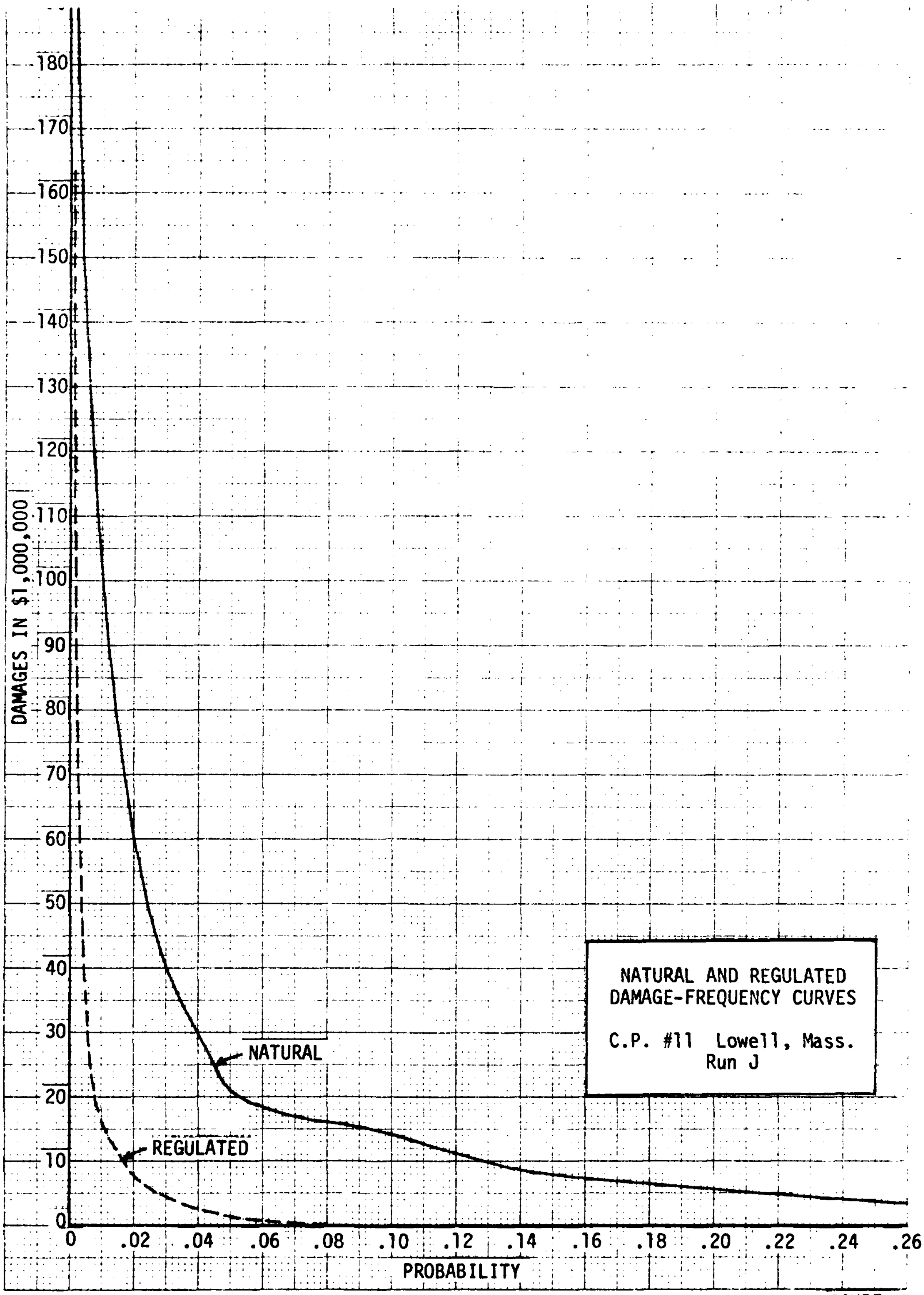
Paper 12

FIGURE 4



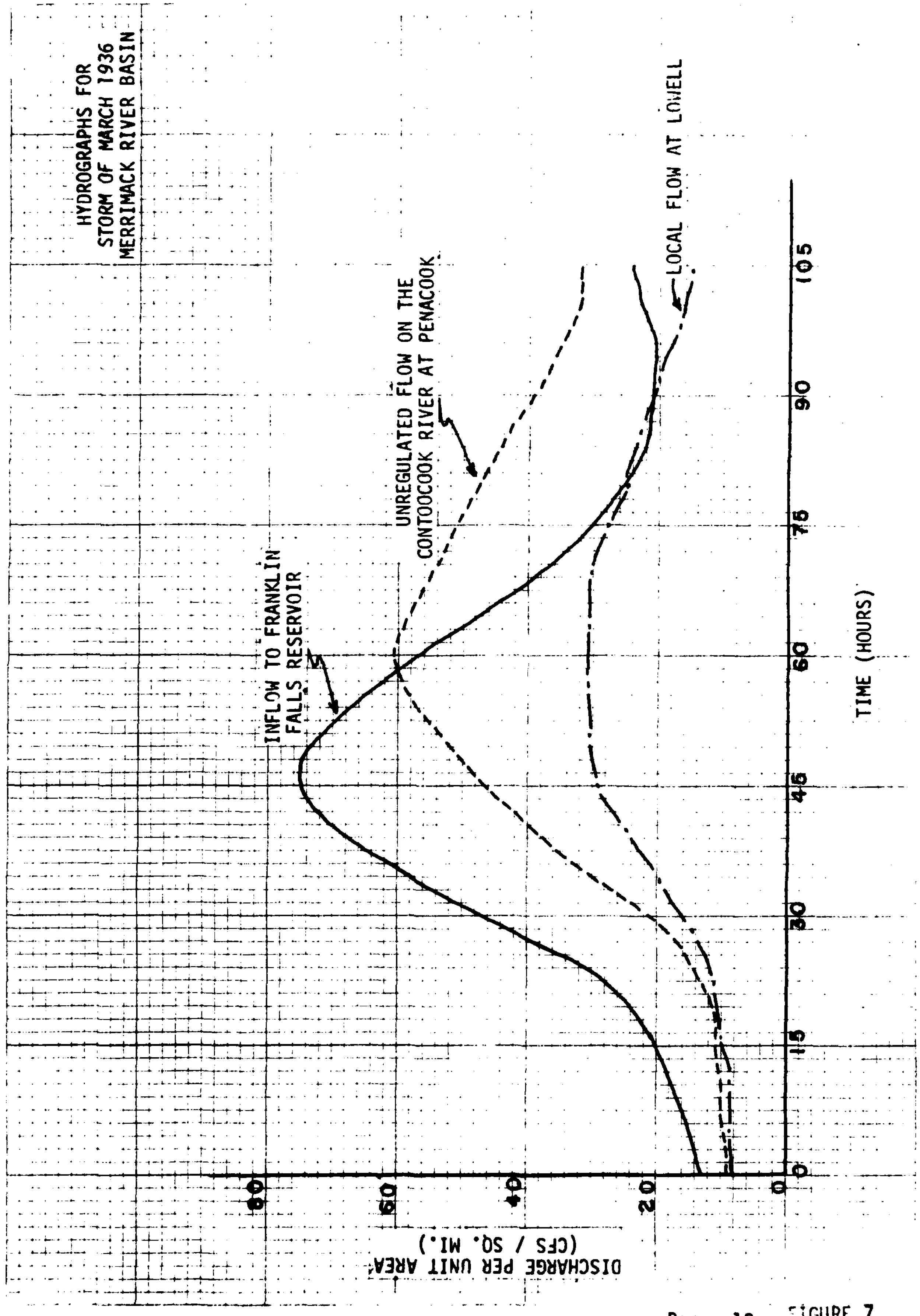
Paper 12

FIGURE 5

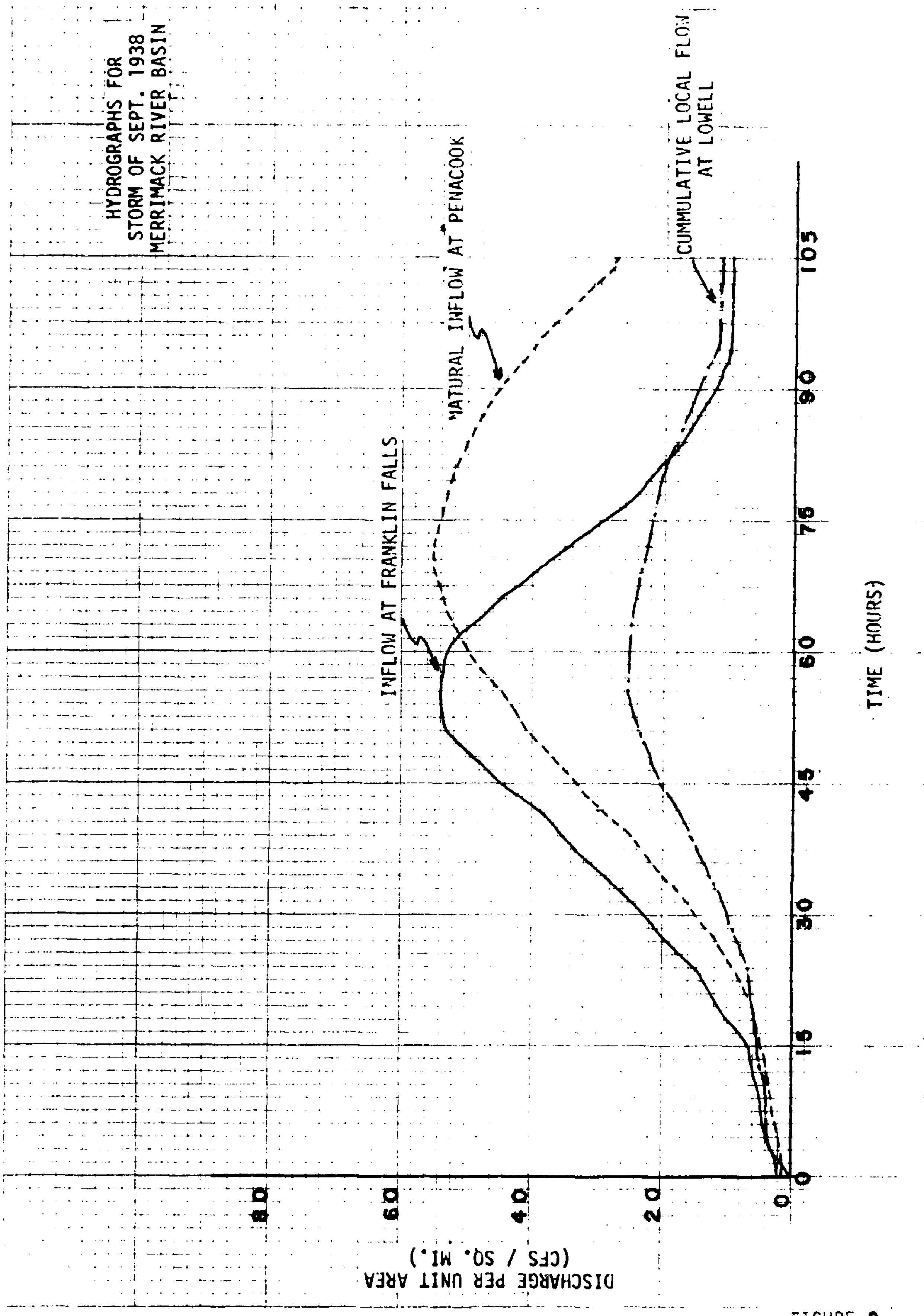


NATURAL AND REGULATED
DAMAGE-FREQUENCY CURVES
C.P. #11 Lowell, Mass.
Run J
DAMAGES IN $1,000,000
PROBABILITY
NATURAL
REGULATED
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26

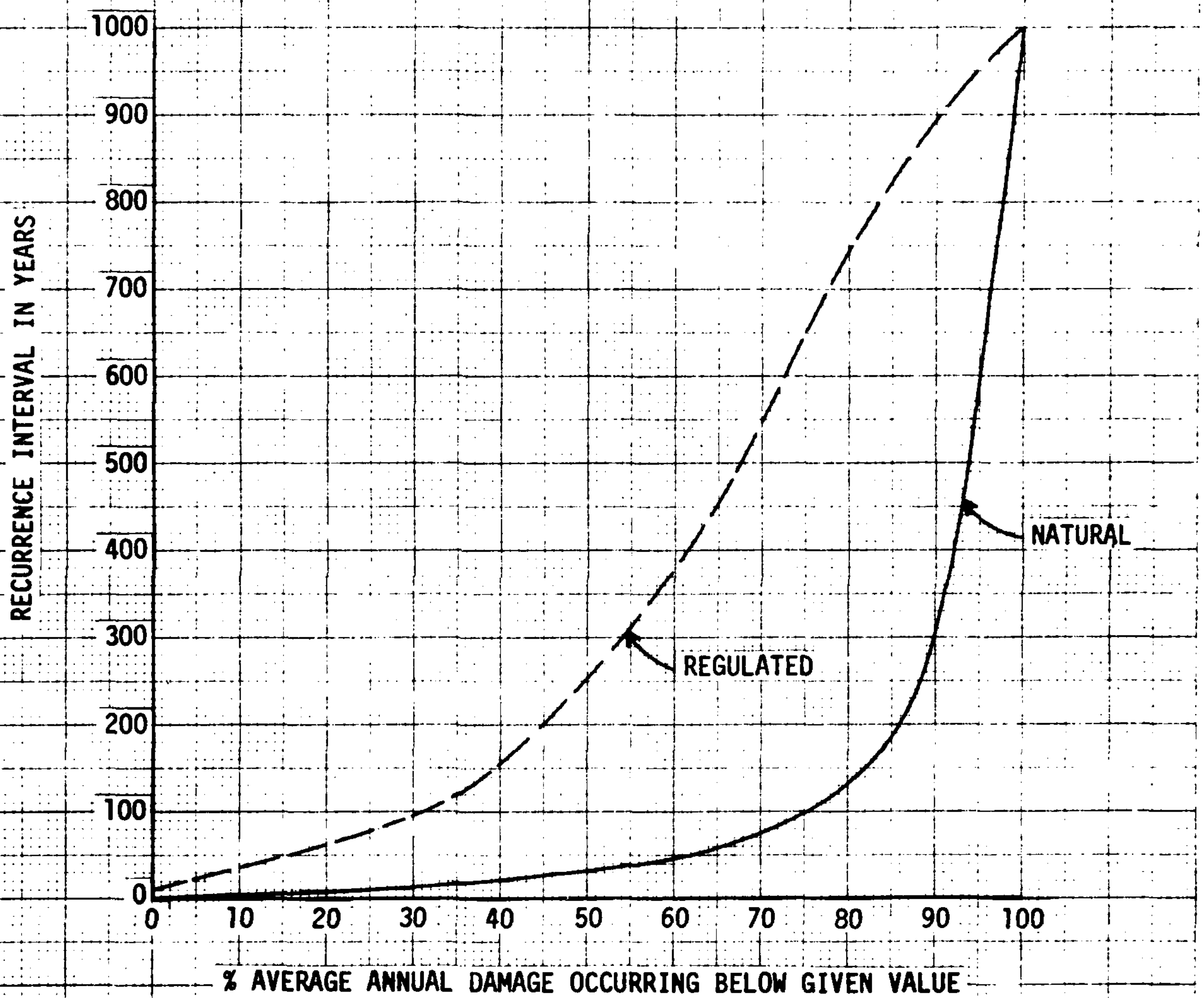
FIGURE 6



Paper 12 FIGURE 7



Paper 12 FIGURE 8



NATURAL AND REGULATED
% AAD-FREQUENCY CURVES

C.P. #11 Lowell, Mass.
Run J

SAMPLE HEC-5C OUTPUT
SINGLE FLOOD SUMMARY

SINGLE FLOOD SUMMARY COPY= 1
COMPUTATION INTERVAL IN HOURS= 3

MERRIMACK RIVER BASIN - FLOOD CONTROL OPERATION
1936 STORM DAMAGE IN THOUSANDS OF DOLLARS
5 RESERVOIRS

***** FLOOD NUMBER 2 *****

LOC=		NONRESERVOIRS	MAX REG Q	MAX NAT	MAX UNC	Q BY RES	NO FLOODS TOTAL	VOL FLOODS TOTAL	NO I FR(
6	6	PETERBOROUGH	5963.	8881.	5312.	651.	34.	71513.	
7	7	PENACOOK	25212.	46800.	9425.	15787.	15.	99079.	
8	8	FRANKLIN JUNC	63748.	83000.	7200.	56548.	30.	460102.	
9	9	GARVINS FALLS	60440.	121068.	18990.	41450.	28.	571844.	
10	10	GOFFS FALLS	73486.	143606.	45971.	27515.	29.	578207.	
11	11	LOWELL	109208.	172939.	88519.	20688.	33.	1414560.	

LOC=		RESERVOIRS	STOR1	MAX STG	MAX LEVEL	EXCEEDED TOP F.C. 1ST PER.	LAST PER.	MAX INFLOW
3	3	MACDOWELL	1453	16074	2.102	24	49	3950
4	4	HOPKINTON	24000	78987	2.022	38	49	17827
2	2	BLACKWATER	9220	45999	2.000	49	49	10850
1	1	FRANKLIN FALL	50000	184953	2.262	24	49	75800
5	5	EVERETT	10000	94028	2.035	37	49	23963

MAX SYSTEM STORAGE= 420041

FIGURE 10 Paper 12

SAMPLE HEC-5C OUTPUT USER DESIGNED

USER DESIGNED OUTPUT

LOC NO=						3.	4.	2.	1.	5.
PER	HR	DY	MO	YR	DW	OUTFLOW	OUTFLOW	OUTFLOW	OUTFLOW	OUTFLOW
1	3	1	0	0	1	650.00	7000.00	2253.20	0.00	0.00
2	6	1	0	0	1	0.00	7000.00	2237.53	1200.81	0.00
3	9	1	0	0	1	0.00	7000.00	2222.10	1640.56	750.00
4	12	1	0	0	1	0.00	7000.00	2206.89	6140.56	903.79
5	15	1	0	0	1	0.00	7000.00	2191.91	10640.56	902.28
6	18	1	0	0	1	0.00	7000.00	2177.16	15140.56	901.79
7	21	1	0	0	1	0.00	0.00	0.00	17059.57	901.84
8	24	1	0	0	1	0.00	0.00	0.00	12559.57	0.00
9	3	2	0	0	2	0.00	0.00	0.00	8059.57	0.00
10	6	2	0	0	2	0.00	0.00	0.00	3559.57	0.00
11	9	2	0	0	2	0.00	0.00	0.00	3345.24	0.00
12	12	2	0	0	2	0.00	0.00	0.00	4181.03	0.00
13	15	2	0	0	2	0.00	0.00	0.00	5080.57	0.00
14	18	2	0	0	2	0.00	0.00	0.00	6037.64	0.00
15	21	2	0	0	2	0.00	0.00	0.00	6753.43	0.00
16	24	2	0	0	2	0.00	0.00	0.00	7608.50	0.00
17	3	3	0	0	3	0.00	0.00	0.00	8737.69	0.00
18	6	3	0	0	3	0.00	0.00	0.00	4237.69	0.00
19	9	3	0	0	3	173.56	0.00	0.00	15338.09	0.00
20	12	3	0	0	3	652.44	0.00	0.00	18433.30	0.00
21	15	3	0	0	3	650.00	0.00	0.00	19598.83	0.00
22	18	3	0	0	3	650.00	0.00	0.00	20878.23	0.00
23	21	3	0	0	3	650.00	0.00	0.00	22960.18	0.00
24	24	3	0	0	3	650.00	0.00	0.00	30545.48	0.00
25	3	4	0	0	4	650.00	0.00	0.00	40829.16	0.00
26	6	4	0	0	4	650.00	0.00	0.00	55388.84	0.00
27	9	4	0	0	4	650.00	0.00	0.00	60728.52	0.00
28	12	4	0	0	4	650.00	0.00	0.00	60548.33	0.00
29	15	4	0	0	4	650.00	0.00	0.00	57320.74	0.00
30	18	4	0	0	4	650.00	1720.98	0.00	52793.29	0.00
31	21	4	0	0	4	650.00	4888.30	0.00	47590.02	582.51
32	24	4	0	0	4	650.00	7784.88	0.00	42397.26	1338.48
33	3	5	0	0	5	650.00	9422.69	0.00	38125.96	1500.00
34	6	5	0	0	5	650.00	10732.69	0.00	33811.98	1500.00
35	9	5	0	0	5	650.00	9184.52	0.00	30500.00	1500.00
36	12	5	0	0	5	650.00	11031.11	0.00	30500.00	1500.00
37	15	5	0	0	5	650.00	11960.31	0.00	30650.23	1500.00
38	18	5	0	0	5	650.00	14171.50	0.00	22852.04	1516.55
39	21	5	0	0	5	650.00	14745.91	0.00	22520.00	1536.38
40	24	5	0	0	5	650.00	15243.95	0.00	22976.00	1547.42
41	3	6	0	0	6	650.00	15523.89	0.00	23400.80	1556.16
42	6	6	0	0	6	650.00	15692.83	0.00	19503.20	1560.89
43	9	6	0	0	6	650.00	15746.59	57.47	24860.00	1561.97
44	12	6	0	0	6	650.00	15688.07	781.98	24860.00	1559.13
45	15	6	0	0	6	650.00	15528.73	1307.58	24860.00	1552.79
46	18	6	0	0	6	650.00	15291.80	1307.58	24860.00	1543.86
47	21	6	0	0	6	650.00	14996.47	1307.58	24860.00	1533.04
48	24	6	0	0	6	650.00	14655.65	1307.58	24500.00	1520.74
49	3	7	0	0	7	650.00	14275.82	1307.58	23700.00	1513.40

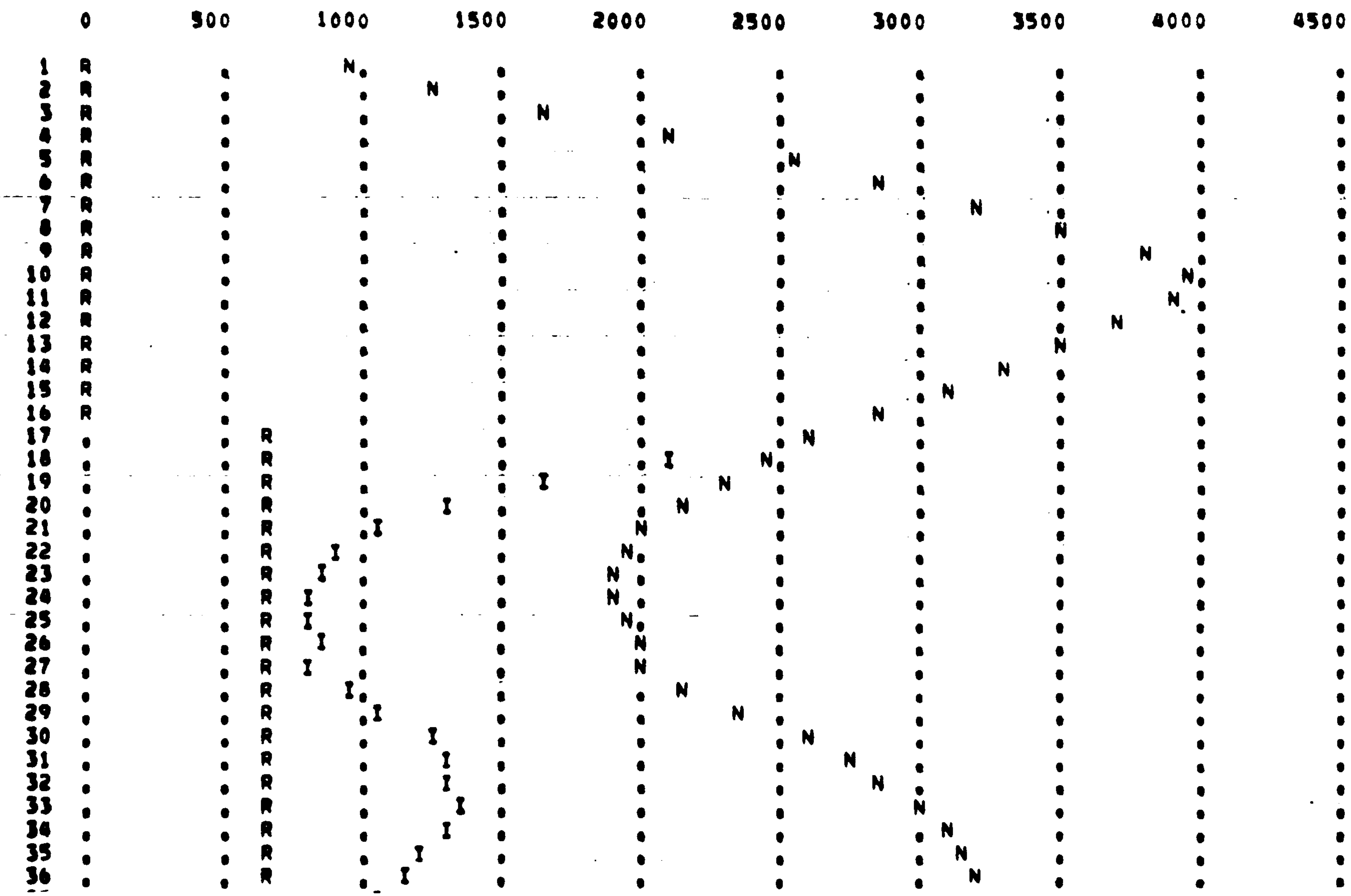
FIGURE 11

INTS (BY PRIORITY)=R=REGULATED,N=NATURAL,L=LOCAL(CUM),I=INFLOW

SAMPLE HEC-5C OUTPUT
PRINTER PLOTS

MAXS 650 3950 3950 =1000

3 MACC[illegible] MX= 3 CH CAP= 650 HOUR=18,DAY=15,MON= 0,YEAR=1[illegible]



INTERACTIVE HEC-5C OUTPUT
"QUESTIONS AND REPLIES"

```
'prout
specify interactive mode and file name   1 ned
********

enter a  ?  when you are uncertain a required response
key the terminal attention key (ESC) once to return to a major branch point or
key the terminal attention key twice in succession to return to the system

********

data file available
 key in  1  to enter data via tablet 1
```

*** * * BRANCH POINT * * ***

```
key in desired function

2

function no  2   .. user determined output format  ..

select period or summary type results  1.  -1.  -11  or ?

1

enter combination(s) or ?. then return carriage



 9.02     9.04     9.01

select output mode p. t. s. or ?

t

copy page and return!
```

INTERACTIVE HEC-5C MENU
FUNCTION SELECTION AND FUNCTION 1 OPTIONS
(PRE-FORMATTED OUTPUT TYPES)

YES	NO	?	DELETE ENTRY	DELETE LINE	KEYBOARD	ESCAPE ESC	CARRIAGE RETURN

* * * BRANCH POINT * * *

FUNCTION	DESCRIPTION
1	DISPLAY DATA AND/OR RESULTS USING STANDARD OPTIONS
2	DISPLAY RESULTS BY USER SPECIFIED CONTROL POINTS AND VARIABLE CODES
3	TRANSFER THE MOST RECENT TIME-SHARE REQUESTED OUTPUT TO THE LINE PRINTER
4	TERMINATE PROCESSING
5	MODIFY HEC-5 INPUT DATA DECK USING THE REVISE PROGRAM
6	DISPLAY OUTPUT WITH BATCH OPTIONS (INVOKE THIS FUNCTION ONLY ONCE)

FUNCTION NO. 1

OPTION	DESCRIPTION
1	display input 1=basic input data
2	display input 2=flow data
4	display input 4=summary of input
5	display normal sequential output by control point

FIGURE 14

INTERACTIVE HEC-5C MENU
FUNCTION 2 (USER DESIGNED OUTPUT)

FUNCTION NO. 2

1	if you want data by period
-1	if you want summary data for reservoirs
-11	if you want summary data for nonreservoirs

VARIABLE CODES

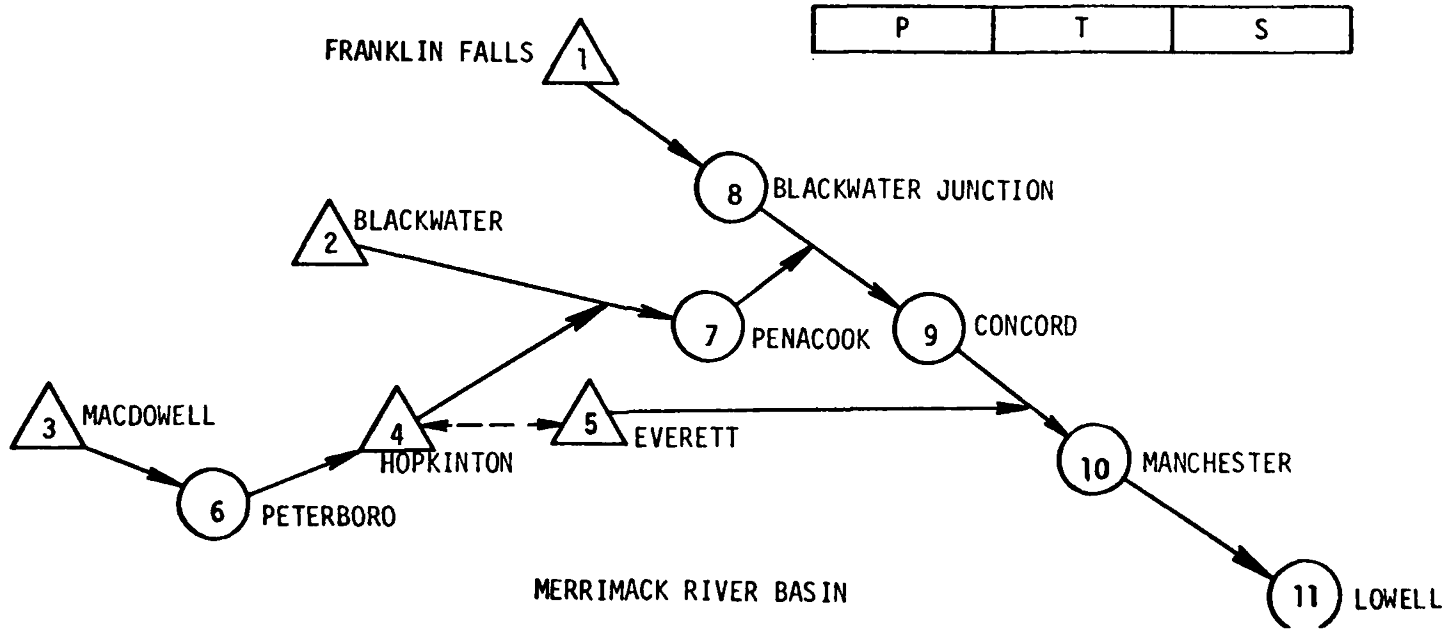
.01	cum local q	.07	min required q	.13	level	.19	q by us res divs
.02	natural flow	.08	shortage	.14	equivalent level	.20	flood by res
.03	diversion q	.09	inflow	.15	power required	.21	evaporation
.04	regulated flow	.10	outflow	.16	power generated	.22	elevation avg
.05	min desired flow	.11	eop storage	.17	channel capacity	.23	pow. shortage
.06	shortage	.12	case=loc typ	.18	q space avail.		

SUMMARY CODES

SUM	MAX	MIN	PD. OF MAX	AVG

SELECT OUTPUT MODE

P	T	S



MERRIMACK RIVER BASIN

FIGURE 15
Paper 12

INTERACTIVE HEC-5C OUTPUT
SAMPLE - USER DESIGNED TABULATION

LOC NO=					9.	9.	9.
PERIOD	MO	DY	YR	HR	NATURAL	REGULATE	CUM LOCA
1	0	5	0	6.	25000.00	27611.16	7044.40
2	0	5	0	9.	26200.00	28692.85	8129.07
3	0	5	0	12.	26350.00	28672.54	8122.60
4	0	5	0	15.	27200.00	29074.60	8555.46
5	0	5	0	18.	28550.00	29142.04	9289.33
6	0	5	0	21.	29900.00	28339.55	9942.61
7	0	6	0	0.	32300.00	28568.95	11330.91
8	0	6	0	3.	34800.00	28543.40	12282.41
9	0	6	0	6.	38200.00	28226.55	13160.84
10	0	6	0	9.	43000.00	28006.42	13850.17
11	0	6	0	12.	48650.00	26980.24	13369.93
12	0	6	0	15.	55700.00	25647.24	12354.63
13	0	6	0	18.	66600.00	26626.40	13533.07
14	0	6	0	21.	82000.00	31347.73	18397.67
15	0	7	0	0.	91000.00	30074.13	17242.24
16	0	7	0	3.	98000.00	28296.41	14630.53
17	0	7	0	6.	110500.00	35262.40	18211.06
18	0	7	0	9.	118000.00	41495.53	18854.33
19	0	7	0	12.	121500.00	46804.25	17815.91
20	0	7	0	15.	121000.00	51689.89	15273.35
21	0	7	0	18.	116500.00	56630.69	11256.75
22	0	7	0	21.	113000.00	64164.27	10226.90
23	0	8	0	0.	106000.00	70323.76	9983.74
24	0	8	0	3.	99200.00	74775.14	10118.43
25	0	8	0	6.	95950.00	77410.36	10181.78
26	0	8	0	9.	91600.00	78036.71	10012.88
27	0	8	0	12.	85800.00	76627.35	9926.28
28	0	8	0	15.	80100.00	73444.46	9748.10
29	0	8	0	18.	71600.00	68048.84	7966.18
30	0	8	0	21.	68500.00	64268.92	7705.23
31	0	9	0	0.	65850.00	62292.93	8839.77
32	0	9	0	3.	62200.00	59402.61	8569.46
33	0	9	0	6.	59500.00	57408.08	8695.51
34	0	9	0	9.	58300.00	56840.88	9739.17
35	0	9	0	12.	57050.00	56277.35	10320.90
36	0	9	0	15.	57800.00	57579.72	12394.33
37	0	9	0	18.	55300.00	55795.46	11141.33
38	0	9	0	21.	54800.00	55749.99	11532.48
39	0	10	0	0.	56800.00	57949.69	14119.64
40	0	10	0	3.	57800.00	59204.33	15692.39
41	0	10	0	6.	57800.00	59542.84	16275.32
42	0	10	0	9.	58700.00	60706.01	17679.72
				SUM =	2854600.00	2031584.50	503516.84
				MAX =	121500.00	78038.71	18854.33
				MIN =	25000.00	25647.24	7044.40
				MPER=	19.00	26.00	18.00

FIGURE 16 **Paper 12**

INTERACTIVE HEC-5C PLOTS
SAMPLE - RESERVOIR DATA

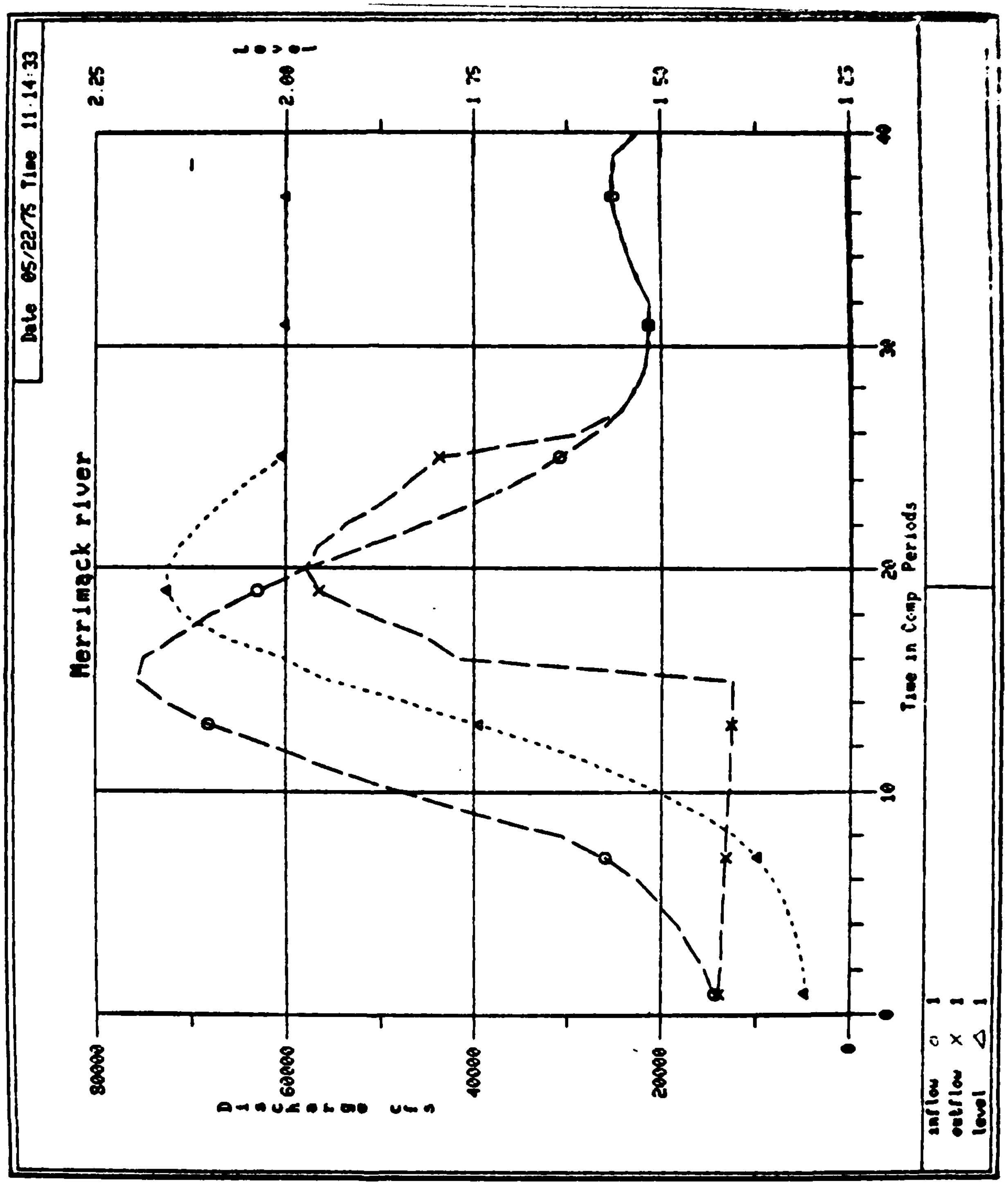


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FIGURE 17

GENERAL SCHEMATIC
REAL TIME-DATA PROCESSING
MERRIMCAK BASIN

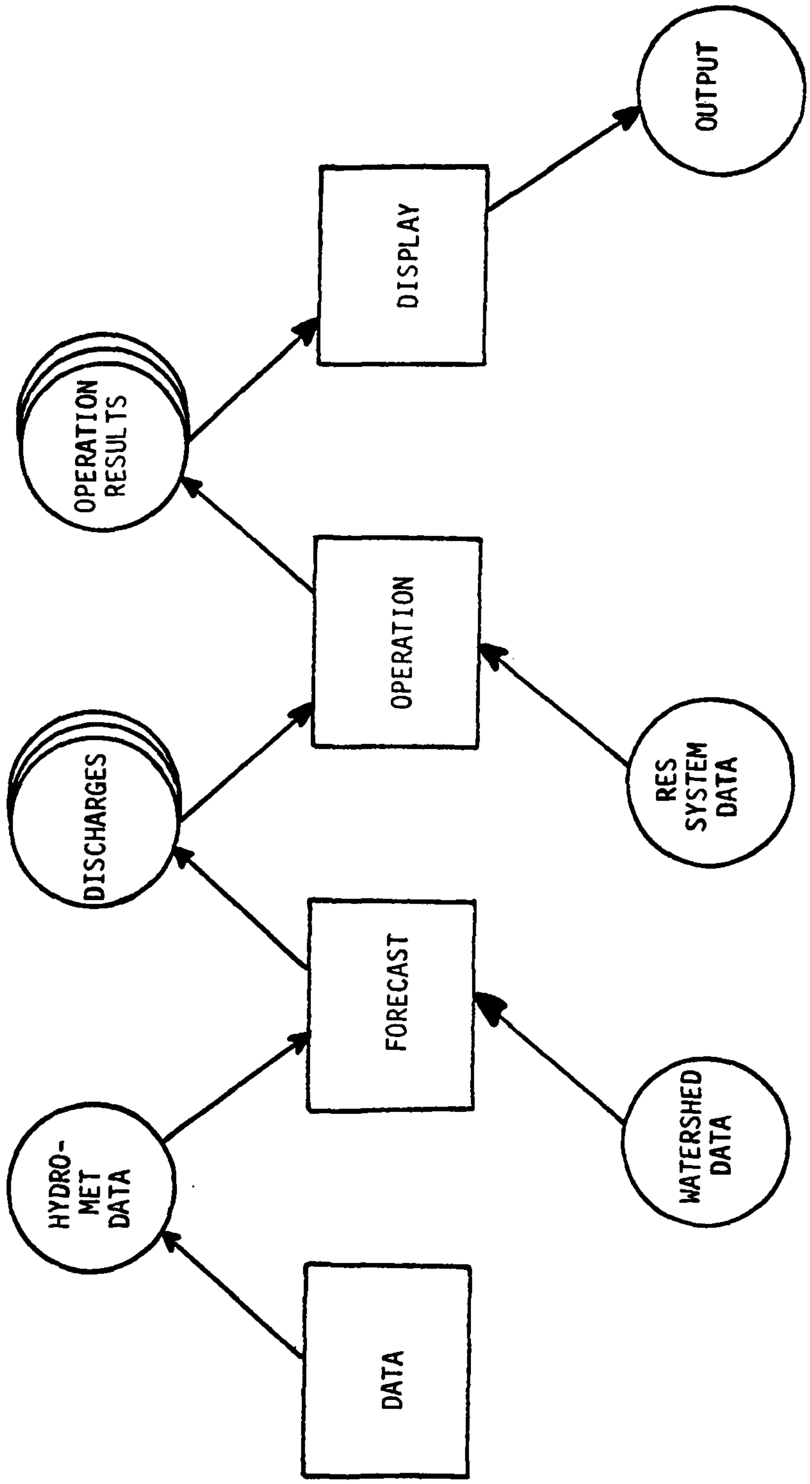
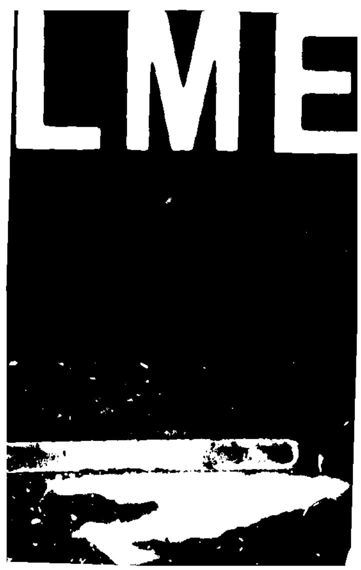


FIGURE 18
Paper 12


LME